JOURNAL
OF THE
WASHINGTON ACADEMY OF SCIENCES

VOL. 13 NOVEMBER 19, 1923 No. 19

GEOPHYSICS.—*Density distribution in the Earth.*[1] E. D. WILLIAMSON and L. H. ADAMS, Geophysical Laboratory, Carnegie Institution of Washington.

There are four principal sources of information concerning the interior of the Earth: (1) the constant of gravitation, from which the total mass and average density of the Earth are determined; (2) the constant of precession and other astronomic and geodetic data from which the moments of inertia of the Earth may be calculated, the moment of inertia allowing important inferences to be drawn concerning the density distribution within the Earth; (3) seismologic data from which the elastic constants of the materials in the interior may be computed; and (4) the known flattening of the Earth as determined from the data of geodesy with which any assumed distribution of materials must harmonize. The first three of these sources, together with the values of the elastic constants of various rocks previously obtained by the authors,[2] provide the basis for the present estimate of the density and composition of the Earth at various depths. The bearing of the above classes of data on the constitution of the Earth's interior will first be discussed briefly.

Mean density of the Earth. The constant of gravitation from direct experimental observation is known to be 6.66×10^{-8} cm^3/g-sec^2. This fixes the average density of the Earth at 5.52, and, as is well known, this fact alone allows certain qualitative inferences to be drawn concerning the interior. The density of any ordinary rock is much less than 5.52; therefore in all probability the density near the center must be considerably higher than 5.52 in order to bring the

[1] Received October 19, 1923.
[2] Journ. Franklin Inst. **195**: 475–529. 1923.

mean density of the Earth to the correct value. A number of empirical laws have been suggested for the increase of density with depth. The best known of these is the one proposed by Laplace. According to this the density at any distance r from the Earth's center is given by the equation

$$\rho = \rho_0 \frac{\sin qr}{qr} \tag{1}$$

in which ρ_0 is the density at the center and q is a constant of which the value is fixed by the known total mass of the Earth. Another well-known relation is that of Roche:

$$\rho = \rho_0 (1 - kr^2) \tag{2}$$

in which k is a constant which also can be determined from the total mass or the mean density of the Earth. Either of these formulas, with the usually assumed surface density 2.7, indicates a density at the center somewhat above 10.

The increased density at the center obviously may be due either to the presence of heavier material, presumably iron or nickel-iron, or to a diminution of volume by the tremendous pressure existing at great depths—or both factors may enter. It has often been assumed that the increase of density with depth is merely the result of the compressibility of the homogeneous material, and that the Laplace law, for example, could be used to calculate the compressibility of the Earth at the surface and in the interior. There is no *a priori* reason why this could not be so, but clearly other lines of evidence must be examined before an answer to this question can be secured.

Moment of inertia of the Earth. It is obvious that for a given mass (or for a given mean density) the moment of inertia depends on the distribution of density,[3] e.g. if there is heavy material at the center and light material at the surface the moment of inertia would be considerably less than if the central density were smaller than that of the surface. The moment of inertia itself is not sufficient to fix

[3] The moment of inertia of a sphere with its mass symmetrically distributed about the center is

$$C = \frac{8\pi}{15} \int \rho \mathrm{d}(r)^5$$

in which ρ is the density at distance r from the center. For a homogeneous sphere this becomes

$$C = \frac{8\pi}{15} \rho r^5 = 0.4\, Mr^2$$

M being the total mass.

the density distribution; it can be used, however, as an important check on a density curve deduced from other considerations. The moment of inertia of the Earth about the polar axis is known to be close to 8.06×10^{44} g-cm^2. Since the moment about the equatorial axis differs from that about the polar axis by only $\frac{1}{3}$ of 1 per cent, very little error is introduced by dealing with a sphere of radius equal to the mean radius of the Earth and having a moment of inertia equal to the value just mentioned.

The moment of inertia of the Earth if of uniform density from surface to center would be 9.7×10^{44}, significantly higher than the true value. In other terms, the moment of inertia of the earth is that of a homogeneous sphere of density 4.6. From this fact follows the qualitative conclusion that in general the density must increase toward the center, in harmony with the inference already drawn from the high density of the Earth as a whole.

Transmission of earthquake waves. The velocity with which earthquake waves are transmitted through the Earth furnishes important information concerning the interior. It has been shown from the theory of elasticity that any disturbance in a sphere of elastic isotropic material should give rise to various kinds of waves traveling with velocities depending only on the density and elastic constants of the material at each point. Waves of two of these kinds pass through the Earth, while the others, which are less simple to analyze, travel over the surface. A seismograph recording the time of arrival of the various waves at some other point would show the arrival first of the two waves passing *through* the Earth and later that of the various surface ones. One of the "through-waves" consists of transverse vibrations and travels with a velocity

$$v_S = \sqrt{\frac{R}{\rho}} \tag{3}$$

while the other consists of longitudinal vibrations and travels with the higher velocity

$$v_P = \sqrt{\frac{K + \frac{4}{3} R}{\rho}} \tag{4}$$

R being the rigidity and K the bulk modulus. These through-waves should theoretically be easily distinguished from the surface-waves by the circumstance that their apparent velocity (i.e., the velocity

obtained by comparing their times of arrival at various points on the surface with the corresponding distances from the origin) should vary with the distance, whereas the velocity of the surface-waves should be constant. The data obtained from seismograms indicate that the material of the earth, except at the surface, may be treated as (megascopically) isotropic. It is fortunate that this is the case, since otherwise the mathematical treatment of seismologic data would be extremely difficult.

Starting from a time-distance curve, that is, the times of arrival of a disturbance at given distances along the surface, by a comparatively simple process one can calculate the elastic constants of the material of the earth at various depths. The steps in the process are as follows: (a) from the slopes of the time-distance curves the apparent surface velocities of each of the varieties of through-waves is obtained; (b) by graphical integration of a certain function of the surface-velocity there is obtained the maximum depth for a wave traveling between two points separated by a specified distance; (c) from a very simple relation the true velocity at this depth is determined; (d) and finally, the bulk modulus K and the rigidity R are calculated from the equations:

$$R/\rho = v_S^2 \tag{5}$$

$$K/\rho = v_P^2 - \frac{4}{3} v_S^2 \tag{6}$$

obtained directly from (3) and (4).

With the time-distance curve given by Turner[4] the velocity-depth curve shown in Fig. 1 was obtained.[5] In this figure the abscissae represent depth in kilometers and the ordinates the velocity in km/sec. This curve closely resembles that obtained by Wiechert[6] and by Knott.[7] The velocity of both kinds of waves increases rapidly at first, and then steadily and almost linearly until a depth of 1600 km is reached, after which the velocity, although nearly constant, shows a tendency to fall off, especially at about 3000 km. By the use of equations (5) and (6) it is evident that these curves could be converted into a compressibility-depth and a rigidity-depth curve—provided that the density were known.

[4] See Davison, *Manual of Seismology*, p. 145.
[5] Further details will be given in a subsequent communication.
[6] Nachr. Kgl. Ges. Wiss. Göttingen. 1907, pp. 415–549.
[7] Proc. Roy. Soc. Edinburgh, **39**: 167. 1918.

Density change due to compression. We shall next use the above results to determine to what extent the higher density of the interior of the Earth may be due to compression alone. The decrease in volume caused by pressure at great depths can not be calculated from the *measured* compressibility of rocks, even if the pressure were known, because the compressibility decreases with the pressure, which at a depth of only a few hundred kilometers is far beyond the range of laboratory measurement. But, fortunately, the velocity of transmission of earthquake waves yields information as to the variation of compressibility ($1/K$) with depth. The values of K/ρ at various depths were calculated by equation (6), and the results are shown in

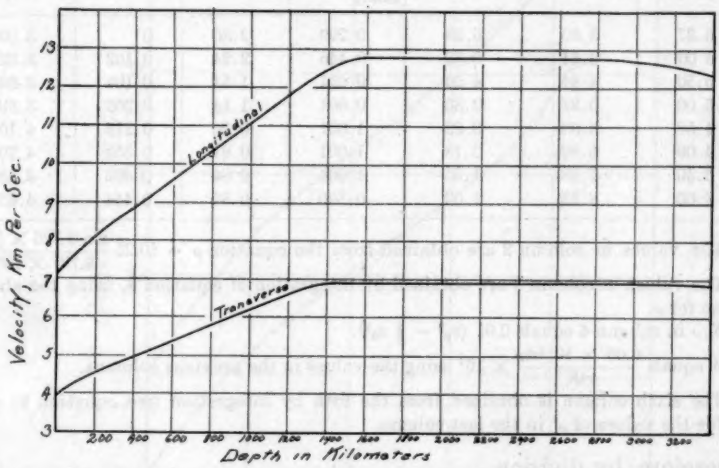

Fig. 1. The velocities of longitudinal and transverse earthquake waves at various depths below the surface of the Earth as calculated from seismologic data.

column 4 of Table 1. Now, it is reasonable to suppose that from this information concerning compressibility it would be possible to determine the aggregate diminution in volume at a given depth on the supposition of a homogeneous earth whose central density is made high by compression and not by a change of composition. We proceed as follows:

In general,

$$\frac{dp}{dr} = -g\rho = -\frac{6.66 \times 10^{-8}\, m\rho}{r^2} \qquad (7)$$

where g is the acceleration of gravity and p is the pressure at distance r from the center; and m, the mass of the sphere of radius r, is obtained from the relation

$$m = 4\pi \int_0^r \rho\, r^2 dr \qquad (8)$$

Now (7) may be written $\frac{dp}{d\rho} \cdot \frac{d\rho}{dr} = -\frac{6.66 \times 10^{-8}\, m\, \rho}{r^2}$

but, on the assumption of homogeneity, $\frac{1}{\rho}\frac{dp}{d\rho} = K$, by definition.

TABLE 1.—FIRST STEP IN CALCULATION OF THE CHANGE OF DENSITY DUE TO PRESSURE AT VARIOUS DEPTHS

10^8 r CM.	ρ LAPLACE	10^{27} m GRAM	$\left(\frac{\text{CM.}}{\text{SEC.}}\right)^2 \times 10^{12}$ K/ρ	A	$\ln \frac{\rho'}{3}$	ρ'
6.37	3.00	5.98	0.299	2.86	0	3.00
6.00	3.61	5.39	0.446	2.24	0.102	3.32
5.50	4.44	4.56	0.651	1.54	0.191	3.63
5.00	5.27	3.86	0.901	1.14	0.261	3.89
4.50	6.08	2.92	1.001	0.96	0.313	4.10
4.00	6.86	2.18	1.001	0.91	0.359	4.29
3.50	7.58	1.55	1.001	0.84	0.402	4.48
3.00	8.25	1.02	0.890	0.85	0.444	4.68

The values in column 2 are obtained from the equation $\rho = 10.25 \frac{\sin 3.726 \times 10^9 r}{3.727 \times 10^9 r}$

The values in column 3 are obtained by integration of equation 8, using the above value for ρ.

K/ρ in column 4 equals 0.01 $(v_p^2 - \frac{4}{3} v_s^2)$.

A equals $\frac{6.66 \times 10^{-8} m\rho}{r^2 K} \times 10^7$ using the values in the previous columns.

The sixth column is obtained from the fifth by integration (see equation 9) and yields the values of ρ' in the last column.

Therefore, by division

$$\frac{d \ln \rho}{dr} = -\frac{6.66 \times 10^{-8}\, m\, \rho}{r^2 K}$$

or

$$\ln \frac{\rho}{\rho_r} = -\int_r^r \frac{6.66 \times 10^{-8}\, m\, \rho}{r^2 K}\, dr \qquad (9)$$

r being the mean radius of the Earth and ρ_r the surface density.

The density-depth relation is obtained from this equation by approximation and repeated graphical integration. First the density at various levels is assumed (consistent, of course, with the known average density of the Earth). The quantity, r^2, is then plotted against r, and m found by graphical integration of equation (8).

Next, the quantity, $m\rho/r^2K$, is plotted against r, and ρ as a function of r determined according to equation (9) by another graphical integration. This first approximation for ρ is used to calculate a new curve for m, which in turn yields a second approximation for ρ. It turns out that the convergence is very rapid, so that with almost any initially assumed values of the density three successive integrations of equation (9) are sufficient.

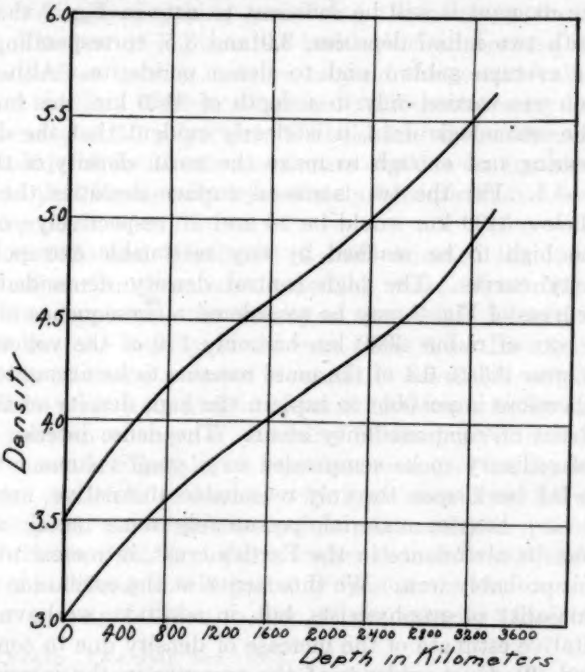

Fig. 2. For two initial densities, 3.0 and 3.5, these curves show the change of density due to compression alone. The values are obtained from the variation of compressibility, which in turn is determined from the earthquake velocity-depth curve.

Table 1 shows the first step of such a calculation, the initially assumed values of ρ being those given by Laplace's equation with a surface density 3.0. From this first step alone it is evident that Laplace's distribution of density is impossible if the condition of homogeneity were fulfilled, i.e. the density according to Laplace increases faster than can be accounted for by compression alone.

The final density curves for two different assumed surface densities (3.0 and 3.5) are shown in Fig. 2. The proper value to take for the

initial density is difficult to determine. It has been placed all the way from 2.7 to 3.7 by various investigators. It is generally agreed that although the average density of surface rocks is from 2.7 to 2.8, corresponding to granite or granodiorite, nevertheless the granitic layer is relatively few miles deep (say 5 to 20); and that underneath this very thin skin of granitic (and sedimentary) rocks lies a more basic material such as gabbro or even pyroxenite or peridotite.

For the moment it will be sufficient to note in Fig. 2 the density curves with two initial densities, 3.0 and 3.5, corresponding respectively to average gabbro and to dense peridotite. Although the calculation was carried only to a depth of 3400 km, this limit being set by the seismologic data, it is clearly evident that the density is not increasing fast enough to make the mean density of the Earth equal to 5.5. For the two assumed surface densities the average density below 3400 km would be 15 and 20 respectively—obviously much too high to be reached by any reasonable extrapolation of the density curves. The high central density demanded by the density curves of Fig. 2 may be considered a consequence of the fact that the core of radius 3000 km has only 1/9 of the volume of the Earth whereas 0.3 to 0.4 of the mass remains to be accounted for.

It is therefore impossible to explain the high density of the Earth on the basis of compressibility alone. The dense interior can not consist of ordinary rocks compressed to a small volume. We must therefore fall back upon the only reasonable alternative, namely, the presence of a heavier material, presumably some metal, which, to judge from its abundance in the Earth's crust, in meteorites, and in the sun, is probably iron. We thus arrive at the conclusion accepted by the majority of geophysicists, but, in addition, we have here (1) a quantitative estimate of the increase of density due to compression alone, and (2) *direct* evidence of the presence in the interior of the Earth of a dense material such as iron.

Effect of temperature. This is a disturbing and uncertain factor. From the known temperature gradient at the surface it follows that the temperature at 100 km depth must be considerably above the melting-point of ordinary rocks; and it seems unlikely that the central temperature can be less than several thousand degrees. The effect of this high temperature on the density is not easily estimated, and might conceivably be very large, but it so happens that the problem is simplified by the fact that at high pressures the expansion coefficient becomes less than at low pressures. Now, the pressure half way down to the center of the Earth is more than a million atmospheres, and

it is not at all improbable that at this pressure the total thermal expansion would be relatively small. For the present, at any rate, we shall ignore the effect of temperature, but with some confidence that in relation to density it is a minor factor.

Previous theories of density distribution in the Earth. Laplace's distribution, already mentioned, should perhaps best be regarded as an empirical relation connecting density with depth, and should not be taken to imply anything concerning the cause of the increased density. The law of Laplace has been criticised because it requires too low a surface density in order to yield the correct value for the moment of inertia. Darwin[8] suggested a different density law with a surface density of 3.7 g. per cc. He held that the sedimentary layer on the outside of the Earth was a mere shell, to be considered separately, and that the density immediately beneath should be taken as the starting point.

Dana[9] in 1873 and Wiechert[10] in 1897 assumed the Earth to be made up of an iron core surrounded by rock. According to Wiechert's[11] later hypothesis the density of the shell is 3.4 and its thickness 1500 km, the density of the core being 8.4. His distribution[12] fits both the mass and moment of inertia of the Earth very well, and the transition point from rock to metal at 1500 km is in fair agreement with the sudden change of direction of the curve of earthquake velocities shown in Fig. 1; but it takes no account of the density due to compression, and fails to explain why there should not be an actual discontinuity at the transition point. At moderate pressures the velocity in basic rocks is notably higher than in iron,[13] and at high pressures this difference will probably increase rather than decrease. Moreover, as may be seen in Fig. 1, the velocity below 1600 km

[8] G. H. Darwin. Proc. Roy. Soc. 1883.

[9] J. D. Dana, *Manual of Geology.* (1873.)

[10] Nachr. Kgl. Ges. Wiss. Göttingen. 1897, p. 221.

[11] Phys. Z. 11: 294. 1910.

[12] It may be noted that on the assumption of a core and a shell each of uniform density the radius and density of the core may be calculated from the known mass and moment of inertia and an assumed outer density by the two equations:

$$\rho_a - \rho_2 = x^3(\rho_1 - \rho_2)$$

$$\rho_m \rho_2 = x^5(\rho_1 - \rho_2)$$

in which ρ_a is the mean density, ρ_m is the density of a homogeneous sphere of moment of inertia equal to that of the Earth, ρ_1 is the density of the core, ρ_2 that of the shell, and x the ratio of the radius of the core to that of the Earth. Thus, if the density of the outer layer is 3.00, its thickness must be 1300 km. and the density of the core is 8.03; and if the outer density is 3.40, the thickness of the shell would be 1600 km. and the central density 8.45.

[13] Adams and Williamson. *Op. cit.*: p. 520.

changes very little—contrary to what might be expected of a *homogeneous* material under a constantly increasing pressure. It may be argued that the effect of temperature in this region may decrease the elastic constants and hence also the velocity. But on any hypothesis the temperature is not increasing rapidly as far down as this, and moreover it seems improbable that increasing temperature would decrease both the rigidity and the bulk modulus by the right amount so that the two velocities would remain so nearly constant.

In recent times Goldschmidt[14] has postulated an arrangement of the matter within the Earth as follows: (1) an outer silicate layer 120 km thick and of density 2.8; (2) a layer of dense silicates (eclogite) extending to 1200 km depth with density varying from 3.6 to 4.0; (3) an intermediate zone of sulfides and oxides of density 5.6 and extending to 2900 km; and (4) a central core of nickel-iron having a density about 8. The average density of this arrangement is very close to the accepted value, and the moment of inertia although 3 per cent too low can be considered in fair agreement. Zoeppritz, Geiger and Gutenberg,[15] and Mohorovičić,[16] and others, have adduced evidence in favor of the existence of various shells or layers in the Earth. For lack of space we can not discuss them here, but will pass on to a statement of the distribution here proposed.

PROPOSED DENSITY DISTRIBUTION

Outermost layer. The average density of the igneous rocks[17] at the surface is about 2.8. Allowing for a small amount of sedimentary rock let us take the surface density as 2.7. The density and basicity of the rocks must increase with depth, the increase being gradual but not necessarily regular. Probably the outer 10 to 20 km has the average composition of a granite or a granodiorite. From the seismographic records of the Oppau explosion Wrinch and Jeffreys[18] found the velocity of the longitudinal waves to be 5.4 km/sec which agrees well with 5.6, the velocity in typical granite at moderate pressures as determined by Adams and Williamson[19] from the elastic constants of the rock. Theoretically the surface velocity can be obtained from the initial slope of the ordinary time-distance curve, but on account of

[14] V. M. Goldschmidt. Z. Elektrochem. **28**: 411. 1922.
[15] Nachr. Kgl. Ges. Wiss. Göttingen. 1912, p. 121.
[16] Beitr. z. Geophysik **13**.
[17] H. S. Washington. Bull. Geol. Soc. Am. **33**: 388. 1922.
[18] Dorothy Wrinch and Harold Jeffreys. Roy. Astr. Soc., M. N., Geophys. Suppl. 1: 15–22. 1923.
[19] *Op. cit.*, p. 520.

the scarcity of reliable observations for near earthquakes the extrapolation of the surface velocity back to zero distance is unsatisfactory and, moreover, as emphasized by Wrinch and Jeffreys, the usual uncertainty regarding the depth of focus would vitiate the results at short distances. From Turner's table the surface velocity of the longitudinal waves seems to be about 7.1 km/sec—between the values for pyroxenite (7.0) and for peridotite (7.2), and distinctly higher than that for gabbro (6.9). Other seismologists give 8.0 km/sec for the velocity just below the "crust." The seismologic data, although not yielding a satisfactory value for the velocity near the surface, seem clearly to indicate a high velocity at a relatively small depth and thus, in harmony with geological evidence, to imply a preponderance of basic material at something less than 100 km. We propose, somewhat arbitrarily, to take 60 km for the thickness of the layer in which the rocks change from acid to basic. The lower limit of this layer may or may not be identical with the depth of isostatic compensation. From gravity measurements in mountainous regions this depth is placed by Bowie[20] at 96 km, but from the data over the whole United States he places it at 60 km. Washington,[21] moreover, finds the average density of various regions on the Earth to harmonize with the average elevation on the basis of isostatic compensation at a depth of 59 km. In any case this layer has a volume of only a few per cent of the total volume of the Earth and its thickness has little effect on the density distribution of the Earth as a whole. The basaltic substratum, postulated by Daly, Wegener, and others, and of great importance in interpreting the geology of the earth's crust, is here merely an incidental feature in the transition from granitic to ultra-basic material.

Basic Layer. Referring again to Fig. 1, one may note that the earthquake velocity curves run regularly and almost linearly from near the surface to about 1600 km depth. It is natural to assume that this region then is a more or less homogeneous material the bulk modulus and rigidity of which increase regularly with pressure. From reasons given below it is probable that the normal density, i.e. the density at low pressures, of this material is 3.3, which corresponds to 3.35 at a depth of 60 km. The density at other depths may be obtained by interpolation between the two curves of Fig. 2. Thus, at 1600 km depth the density has increased by compression to 4.35.

[20] W. Bowie. U. S. Coast & Geod. Survey, Sp. Publ. No. 40: 133. 1917.
[21] H. S. Washington. *Op. cit.*, p. 405.

The normal density 3.3 corresponds to a pyroxenite or a peridotite. Throughout this whole region the temperature must be very high, and it is difficult to avoid the conclusion that this layer is all at a temperature above its melting point, its high rigidity being maintained by pressure.[22] Both the density and the earthquake velocity will probably be somewhat smaller in such a glassy material than in a crystalline layer of the same composition, but the difference can hardly be great enough to nullify the evidence in favor of an ultrabasic layer.

It has been suggested that meteorites should have the same average composition as that of the Earth or of any other part of the solar system. Now this average composition[23] (due account being taken of the proportion in which stony and metallic meteorites are seen to fall) corresponds to: olivine, 35; aluminous pyroxene, 42; anorthite, 4; troilite, 5; nickel-iron, 13. The silicate portion is principally an olivine-pyroxene mixture and thus is essentially a peridotite, and should have nearly the same density and compressibility as that postulated for the basic layer.

Pallasite layer. A remarkable feature of the earthquake velocity curves (Fig. 1) is the small amount of change beyond a depth of 1600 km. From compressibility measurements the velocity of the longitudinal waves in iron at moderate pressures is 6.0 km/sec, whereas the velocity in peridotite is 7.2. At high pressures the difference will probably be greater. This circumstance immediately suggests that the nearly constant velocity below 1600 km may be due to a gradually increasing amount of metallic iron mixed with the siliceous rock. The normal tendency for the velocity to increase with depth is thus offset by the admixture, in gradually increasing amount, of iron (or nickel-iron).

The material in this region may be thought of as resembling certain meteorites consisting of a heterogeneous mixture of silicates and metallic iron which is called pallasite. The lower limit of this zone of incomplete segregation is thought to lie at about 3000 km depth where the velocity shows distinct evidence of falling off.

Central metallic core. The remaining part of the Earth consists, beyond reasonable doubt, mainly of iron or nickel-iron with density

[22] Cf. R. A. Daly. *Igneous Rocks and their Origin.* (New York, 1914.) p. 172.

[23] Cf. O. C. Farrington. Field Columbian Museum, Geol. Ser., Vol. 3, Publ. No. 120: 211–13. 1911.

W. D. Harkins. Journ. Am. Chem. Soc. 39: 864. 1917.

appropriate to the conditions of pressure (and of temperature) existing in the central region. This density should increase toward the center, but by a relatively small amount.

Now, if we assume (a) that the density in the surface layer varies linearly with depth from 2.7 to some chosen density ρ_s at the top of the basic layer, (b) that in this basic layer the density change can be calculated by interpolation between the two curves of Fig. 2,

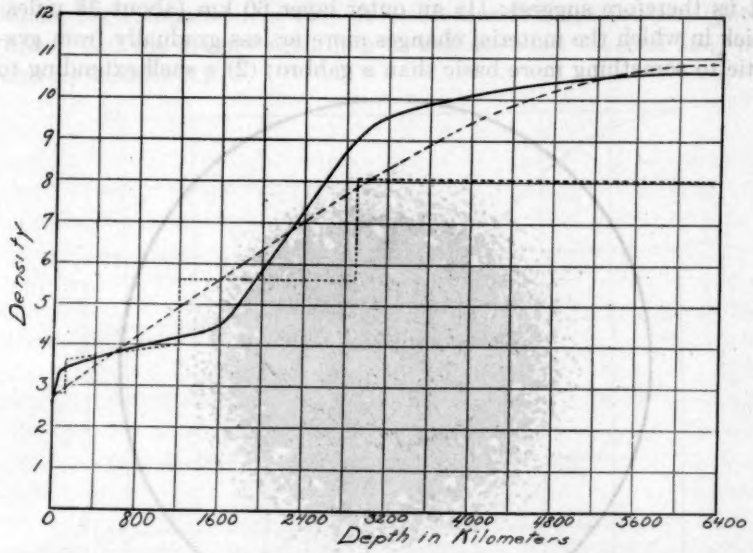

Fig. 3. The density of the Earth at various depths according to the present estimate (full-line curve). For comparison Goldschmidt's distribution (dotted lines), and the density law of Laplace (broken line) are included.

(c) that in the pallasite layer the density changes linearly with depth (the simplest assumption), and (d) that in the central core the density changes parabolically[24] (the simplest assumption compatible with the necessary condition that $dp/dr = 0$ at the center), the fact that the distribution must satisfy the known mass and moment of inertia of the whole Earth, allow us to solve two simultaneous equations and find the density distribution in the pallasite layer and in the central core. If this calculation be carried out for various values of ρ_s, it is found that ρ_s must be close to 3.35 in order to yield a reasonable density-variation in the central core. The value 3.45 demands that

[24] That is, according to the relation $\rho = k_1 + k_2 r^2$, k_1 and k_2 being constants.

in the core the density *decrease* with depth. On the other hand the value 3.25 leads to an unreasonably high density at the center. For this reason the density at the top of the basic layer has been taken as 3.35, corresponding, as stated above, to a normal density 3.3 and to a density 4.35 at 1600 km. The density of the iron would then be 9.5 at 3000 km and 10.7 at the center.

As a tentative distribution and as a basis for future speculation let us therefore suggest: (1) an outer layer 60 km (about 35 miles) thick in which the material changes more or less gradually from granitic to something more basic than a gabbro; (2) a shell extending to

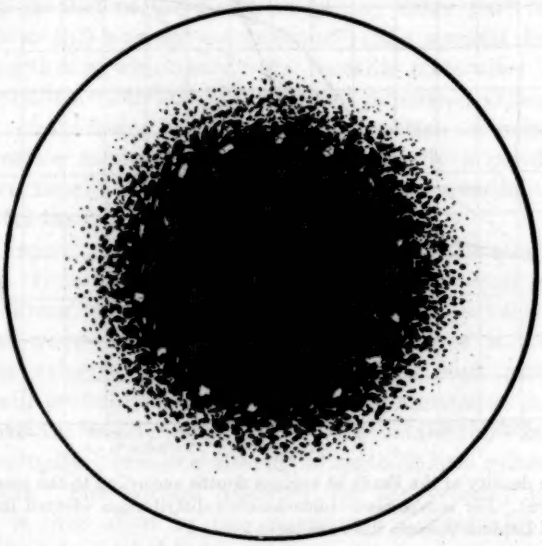

Fig. 4. Diagram intended to suggest the segregation of metallic iron toward the center, and the zone of pallasite (mixture of iron and silicates) surrounding the central core.

a depth of 1600 km, consisting of peridotite, that is, mainly of iron-magnesium silicates and having a normal density 3.3 and a density at 1600 km of 4.35; (3) a shell of pallasite reaching to 3000 km below the surface, in which silicate rock is gradually replaced by metallic iron (or nickel-iron) not yet completely segregated, the density in this shell changing gradually from 4.35 to 9.5; and (4) below this layer of pallasite a central core of nickel-iron of nearly constant density—varying from a little below to a little above 10. The existence of other layers or of other discontinuities is neither affirmed nor

denied. The proposed density distribution merely attempts to harmonize certain known facts regarding the mass and moment of inertia of the Earth, the velocities of earthquake waves, and the compressibilities of rocks.

The distribution here described is shown graphically in Fig. 3 (full-line curve). At the boundary between the various zones the corners are arbitrarily slightly rounded. This diagram also contains, for comparison, a plot of Goldschmidt's distribution (dotted lines), and the density according to Laplace's law (dashed line) with surface density 2.7.

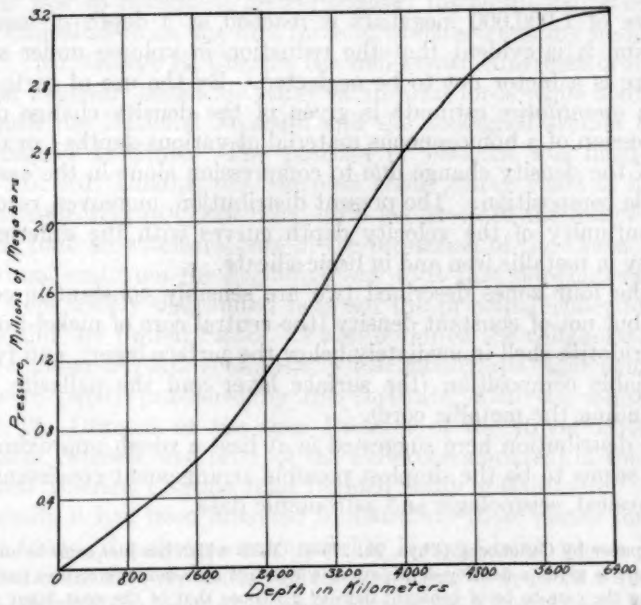

Fig. 5. Pressure as a function of depth, derived from the full-line curve of Fig. 3.

Fig. 4 is intended to illustrate the segregation of iron toward the center and the fringe of pallasite surrounding the iron core. The depth of the surface layer—60 km—is shown to scale by the thickness of the outer circular line.

Pressure in the Earth. The pressures corresponding to the present density distribution were obtained from the equation

$$p = \int_{r}^{\infty} \frac{6.66 \times 10^{-8}\, m\, \rho}{r^2} dr$$

by graphical integration, m having previously been determined by another graphical integration according to equation (8). The pressures at various depths are plotted in Fig. 5. At the center the pressure is 3.18 millions of megabars, remarkably close to the value obtained from Laplace's law (3.08 million megabars) when the surface density is 2.7.

SUMMARY

For the density and composition of the Earth at various depths there is here proposed a distribution which takes into account the density change due to compression alone. When it is noted that a pressure of 1,000,000 megabars is reached at a depth of less than 2400 km, it is evident that the reduction in volume under such a pressure is a factor not to be neglected. By the use of earthquake data a *quantitative* estimate is given of the density change due to compression of a homogeneous material at various depths—or of that part of the density change due to compression alone in the case of a variable composition. The present distribution, moreover, reconciles the continuity of the velocity depth curves with the difference in velocity in metallic iron and in basic silicate.

Of the four zones described two are sensibly constant in composition but not of constant density (the central core of nickel-iron and the peridotite shell immediately below the surface layer), and two are of variable composition (the surface layer and the pallasite fringe surrounding the metallic core).

The distribution here suggested is at best a rough approximation, but it seems to be the simplest possible arrangement consistent with the physical, seismologic and astronomic data.

In a paper by Gutenberg (Phys. **24**: 296–9. 1923) which has just come to our attention, there is given a density-depth curve which like ours consists of four parts. By assuming the core to be of constant density 2.3 times that of the next layer (also of constant density), Gutenberg calculates that the density of the "Mantel," extending from 60 km to 1200 km depth, varies from 3½ to 4½. This estimate of the density change in the outer parts of the Earth is strikingly like our estimate obtained directly from compressibility and involving assumptions quite different from those of Gutenberg.

BOTANY.—*Note on plants collected in tropical America.* H. PITTIER.

Between October 1887 and the present time, I have collected about 18,000 plants in Mexico, Guatemala, Salvador, Honduras, Costa Rica, Panama, Colombia and Venezuela. These plants have been numbered in two series, and, as the numbers of the one series are

frequently confused with those of the other, a short explanation may be helpful to botanists who have to cite any of them.

The first series was started a few days after my arrival in Costa Rica in October 1887. At that time, I proposed to the Costa Rican Government that it conduct a general survey of the natural products of the country, to be carried on simultaneously with the preparation of a topographic map. The idea was favorably considered and resulted in the organization of the Physico-Geographical Institute of Costa Rica, of which I was director until about 1903, and the decline of which began with my departure for the United States. The Institute as planned was to consist of meteorological, topographical, geological and botanical sections, the first three of which were in my immediate charge. Mr. George K. Cherrie, the well-known American ornithologist and explorer, began his study of tropical birds while connected with both the National Museum and the zoological section of the above-named Institute. The position of botanist was filled by a Swiss, Mr. Ad. Tonduz, who devoted about thirty years of his life to plant collecting in Costa Rica, until his death in the fall of 1921. I myself took an extensive part in the formation of the Costa Rican Herbarium, and from the beginning saw to it that duplicates of the plants were widely distributed between the principal collections of Europe and the United States. I also obtained the collaboration of a large number of plant specialists, whose monographs and enumerations were partly published by the Institute, with the assistance, first of Th. Durand, at the time Director of the Royal Botanical Gardens of Brussels, and later, of the well-known student of the flora of Central America, Captain John Donnell Smith of Baltimore.[1]

Originally it had been intended to distribute these plants through my late friend, the above-mentioned Th. Durand, with whom I had collaborated in the preparation of the *Catalogue de la Flore Vaudoise*, and who certainly succeeded in awakening in me a live interest in the flora of the country in which I had lately established myself. Labels were printed with the heading *Plantae Costaricenses Exsiccatae*, which explains the mention of plants under that designation in some publications. It was soon found, however, that this plan did not work, and after that, the distribution was made directly from San José. New labels were prepared with the heading *Herb. Inst. phys.-geograph. costaric.*, and these were used, not only for the newly collected plants, but also for the whole series, which includes in all about 23,000 num-

[1] See DURAND, TH. et PITTIER, H., *Primitiae Florae Costaricensis* vol. 1, Brussels, 1891–1893; vol. 2 (edited by H. Pittier alone), San José, 1898–1900.

bers. Besides the assistance of Mr. Tonduz, the Institute had the active collaboration of a number of collectors, among whom were the late Prof. Paul Biolley of Neuchâtel, Switzerland, one of the most efficient teachers brought into Costa Rica by the Government of this latter country, Charles Wercklé, an erratic but very keen-eyed botanist, C. Brade, etc., and, among the natives, J. J. Cooper, Anastasio Alfaro, Carlos Brenes, Otón Jimenez, and perhaps a few others. The collecting was continued for several years after I left the country, until the ultimate numbering went up, if I am not mistaken, to about 23,000. Of these, I estimate that about a fourth part was collected by me, half by Tonduz, and the rest by our other co-workers. Of course, every label bears the name of the collector, which fact was the origin of a certain confusion which was increased when I started my own series after I went to Washington. This latter series includes, up to the present date, 11053 numbers, and contains plants from every country of continental America, from Central Mexico to Venezuela, the result of about twenty-two years' explorations.

The most complete set of the Costa Rican collection is probably that of the United States National Herbarium in Washington, which, of course, has also all the plants I brought together while in the service of the United States Department of Agriculture, and the most complete set of my Venezuelan collections.

The botanical exploration of Costa Rica revealed that country as an astonishing center of endemic development for a considerable number of genera and families, and furnished also a large quota of new species. The same can be said of certain parts of Panama, such as the high mountains of Chiriqui and the lowlands of Darien, so that the collection of types of the National Herbarium has been, and is still being, considerably increased by the additions proceeding from these countries.

The plants which form both collections have been, as mentioned above, very often designated so as to cause mistakes and confusion. The first series is that of the *Physico-Geographical Institute*, and the only right way of citing the plants belonging to it is by mentioning this fact. For instance, we would have:

Calathea macrosepala K. Schum.—La Verbena de Alajuelita, near San José, 1000 m., in ditches (*Pittier, Inst. Phys.-geogr. cost.* 8832); near Turrialba, 570 m. (*Tonduz, Inst. Phys.-geogr. cost.* 8310), etc.

Mentioning the first specimen as Pittier no. 8832, as it is done in Schumann's monograph of the *Marantaceae*,[2] is misleading, because the

[2] In ENGLER, *Pflanzenreich*, Heft IV, **48**: 84. 1902.

real *Pittier* no. 8832 in my own series is a *Prestonia*. Unless I am mistaken, Tonduz himself started a new series during the short stay, interrupted by his death, in Guatemala. To continue the erroneous system of numbering the collections in the formation in which I participated, would result, in the end, in thousands of such mistakes, and that is why I have thought it convenient to give the above explanations, which should be put into the hands of all botanists who are interested in the flora of Central America and the northern part of South America.

SCIENTIFIC NOTES AND NEWS

The following resolution was adopted by the Board of Managers of the Washington Academy of Sciences at a meeting held October 29, 1923:

Whereas, The work of scientific men has contributed enormously to the welfare of the human race and especially to the people of the United States of America, and

Whereas, The government of the United States has recognized the importance of scientific investigations and research by the creation of many scientific bureaus, and has appropriated large sums of money for carrying on their work which has been most beneficial to the health, industries, and commerce of this country, and

Whereas, Our people should be kept informed promptly and fully of the progress made and results accomplished by the scientific organizations of the government, and

Whereas, The members of the government engaged on scientific activities can only function to the best advantage by having conferences with scientific men of this country not in government service and with such men of other countries, and

Whereas, This contact can only be gotten by attendance at scientific gatherings in this country and abroad; therefore, be it

Resolved, That the Washington Academy of Sciences hereby petition and urge the President, the heads of departments of the federal government, and the Congress of the United States to give the welfare of science in the United States their earnest consideration and assistance; and to provide by law and by appropriation of the necessary money for the attendance of such scientists of the government as heads of departments may designate at scientific congresses, conventions, and meetings in this country; and for the attendance of such scientists of this country, both in the government and in private life, as may be recommended to the Department of State by competent authority and approved by the head of that Department or the official acting for him, as representatives of the United States of America at international scientific congresses, conventions, and meetings. These appropriations would be exceedingly small as compared with the returns from them in great benefits to scientific advance in America and hence to the promotion of the national welfare.

Be it further resolved, That a copy of these resolutions be sent to the President of the United States, the head of each of the executive departments, the President of the Senate, and the Speaker of the House of Representatives, and that they be published in the Journal of the Washington Academy of Sciences.

Dr. R. B. SOSMAN, of the Geophysical Laboratory, Carnegie Institution of Washington, has been appointed by the National Research Council as American member on the permanent committee for the standardization of physico-chemical symbols of the International Union of Pure and Applied Chemistry. The other members of the committee are: Prof. ERNST COHEN, University of Utrecht, chairman; Prof. ALEXANDER FINDLAY, University of Aberdeen, and Prof. CHARLES MARIE, Sorbonne.

Dr. ARTHUR L. DAY, Director of the Geophysical Laboratory and Chairman of the Carnegie Institution's Advisory Committee in Seismology, gave the opening lecture of the Franklin Institute series for 1923–24 on October 17, 1923. The subject of the lecture was *Earthquakes and volcanic eruptions.*

Dr. HENRY S. GRAVES, dean of the Yale School of Forestry, formerly chief of the United States Forestry Service, has been elected provost of Yale University.

Arrangements have been made with the Radio Corporation of America for a number of short talks on the Smithsonian Institution and its branches to be broadcasted from Station WRC. The first of these talks, on *The Smithsonian Institution, its history and functions,* was given by AUSTIN H. CLARK on October 19. The second, on *The Bureau of American Ethnology; what it is and what it does,* was given by Dr. J. W. Fewkes on October 22. Other subjects are *The Natural History Museum, The Arts and Industries Museum, The Zoological Park, The Astrophysical Observatory,* and *Smithsonian Explorations.* It is estimated by officials of the Radio Corporation that these talks reach an audience of nearly 2,000,000 people, and cover an area 1800 miles in all directions from Washington.